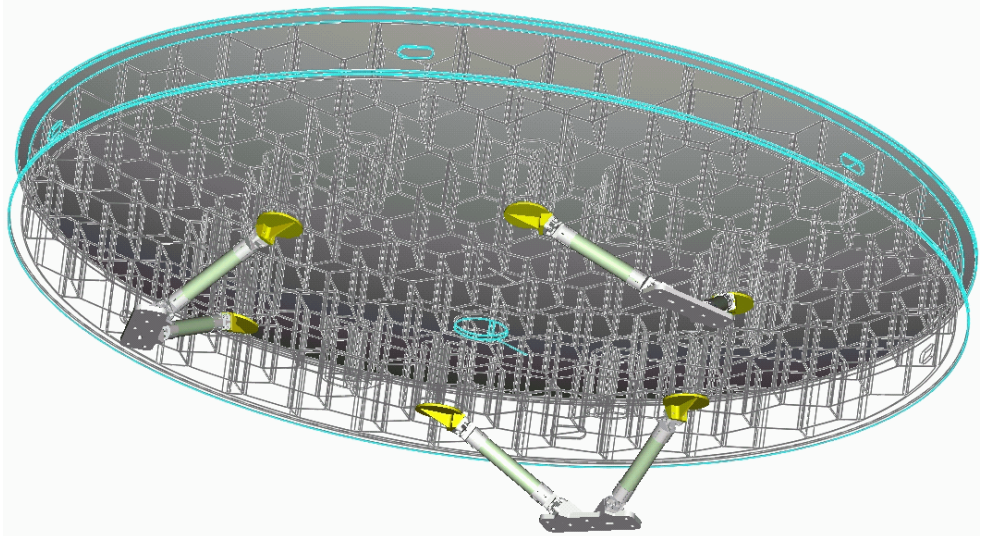
KEPLER PHOTOMETER

Primary Mirror Assembly

Metrology and FEA Analysis of Zero-Gravity Figure



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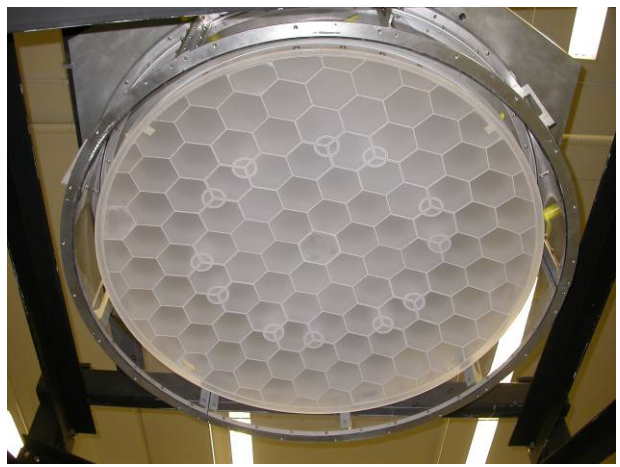
Overview

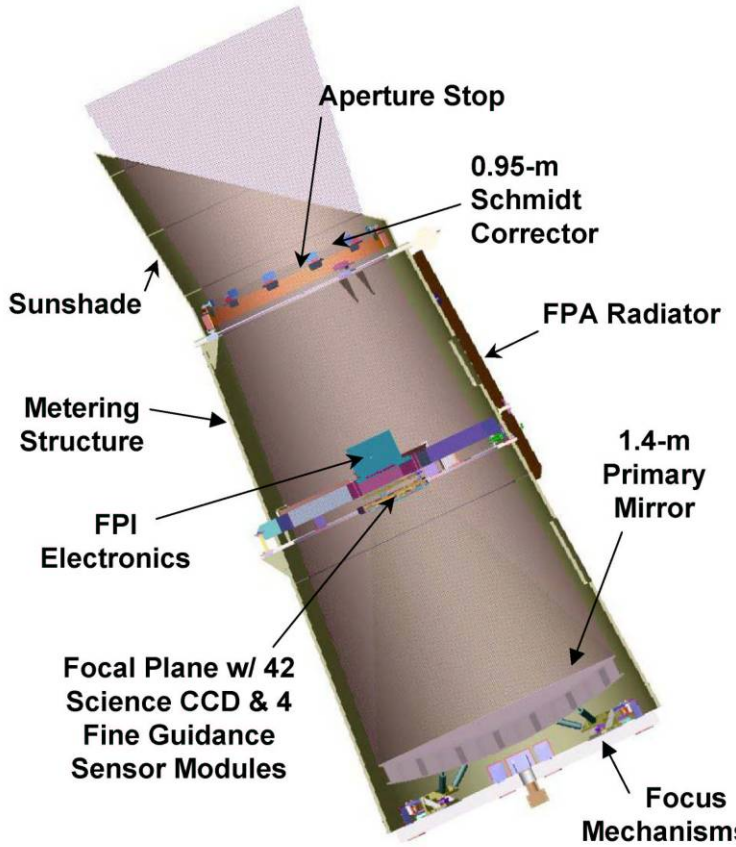
- Brief description of Kepler Space Photometer
- Brief description of L-3 Designed Primary Mirror Assembly (PMA)
- Primary Mirror (PM) fabricated profile
- Comparison of interferometric tests with Finite Element Analysis (FEA) predictions shows good agreement < 10% residual
- Testing shows successful assembly of PMA
- Summary



Kepler Photometer

- Mission to search for Earth size planets
  - 170,000 photometric objects
  - Observes same area of sky for 4 years
    - Look for planetary transits of stars
  - Kepler Photometer Details at http://kepler.nasa.gov/
- Schmidt Optical Design
  - 0.95 meter diameter Schmidt Window
  - 1.4 meter diameter Primary Mirror
  - 100 square degree field of view
- Operates -5^{0}C to -55^{0}C

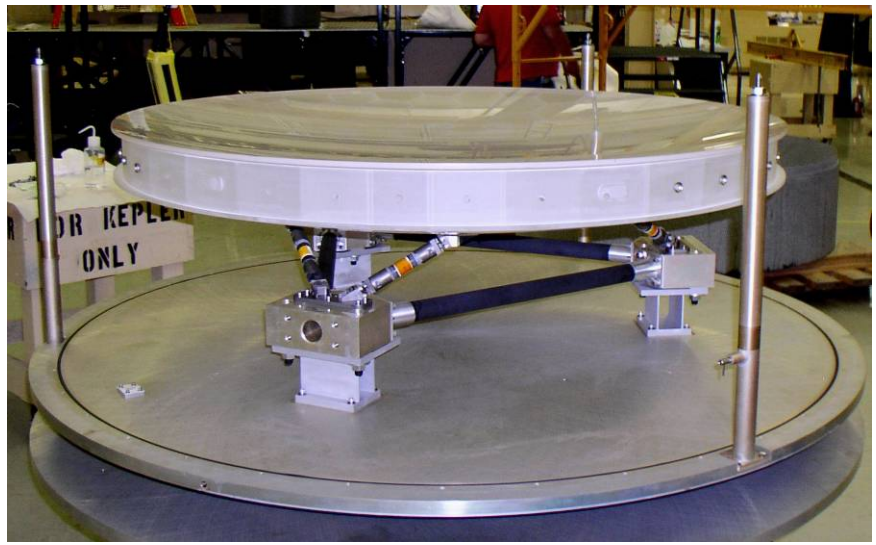
Photometer Architecture



- Two additional electronic boxes mounted to spacecraft (CSP and RPE)
- Focal plane operated at –95° C reduced dark signal and radiation degradation effects
- Field flattener lenses integral to CCD modules provides bandpass filters and CCD radiation protection
- Focus mechanisms at primary mirror mount provide focus / tip-tilt correction for metering structure CTE/CME effects
- Stray-light controlled by baffled GFCE honeycomb metering structure
- Exterior MLI blankets control thermal gradients on optics
- Active heater control on focal plane controls focal plane to ±0.1° C.

Kepler Primary Mirror Assembly

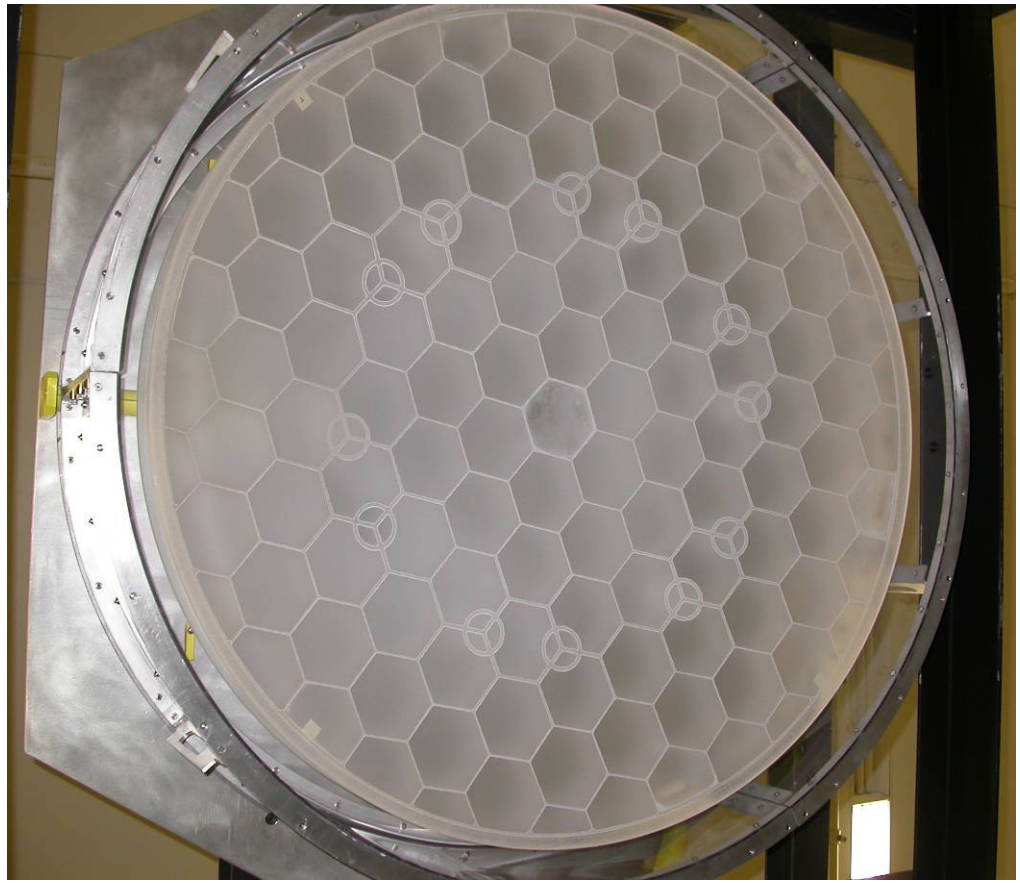
- PMA designed and analyzed by L-3
  - 6 Bonded invar pads on back of PM
  - 6 graphite epoxy struts
  - 3 bipod attachments to focus mechanism or strong back for PMA testing and shipping
- Light weighted PM
  - Designed by L-3
  - Corning ULE blank
  - Figured by L-3



PMA on shipping container base

Light Weighted Primary Mirror

- Frit bonded ULE Primary
- 1.4 meter diameter CA
- Reinforced Bond sites for Invar pads
- No spare PM
  - Careful for good margins
  - Redundant Bond sites
    - 6 Primary
    - 6 Alternate



Overview of Large Optics Metrology

- Testing difficult because large light weight mirrors distort
- Multiple tests used to assure correct Zero-G figure
  - Air bladder
  - Counterweighted zero-G mount
  - PMA vertical testing - looking up and looking down
  - PMA horizontal testing
- FEA analysis predicts 1g surface error based upon
  - As built PM dimensions for correct mass distribution required
  - Accurate measurement of weight
- Tooling designed and implemented carefully
  - Must be repeatable for each iterative test
  - Calibrate design residuals, where possible
- Interferometry
  - Average data to minimize thermal and vibrational noise
    - Each position had 100 frames of data over 30 minute - thermal noise < 0.004 waves
    - Multiple PM orientations, where possible, self calibrate low frequency setup errors
    - Total test time over 1 hour
    - Final noise test noise < 0.007 waves RMS

Comparison of Optical Test Methods

	Air bladder	Counterweighted	PMA vertical	PMA horizontal
Analysis				
Surface RMS	0.009 λ	0.028 λ	0.285 λ	1.052 λ
Surface P-V	0.054 λ	0.156 λ	1.309 λ	4.03 λ
Model error				
Surface RMS	0.026 λ	est. 0.016 λ	0.021 λ	0.033 λ
Type	Symmetrical	Asymmetrical	6 support points	Astigmatism 6 support points
Difficulties	Uniformly Curved bladder to match PM	Point support yields high frequency highs	Analysis straight forward	Analysis straight forward
Implementation	Erroneous force at OD of PM - Uncertainty in symmetrical errors	Careful adjustment of each counter weight to match actual weight of PM	Simple to implement	Horizontal testing astigmatism on PM contaminated by air.
Interferometry	Difficult due to vibrations. Requires 3 hard points for vibrational stability	Vibrationaly stable. Loads monitored at 3 points.	Interferometry mildly difficult with large P-V	Interferometry Difficult with Large P-V
Use at L-3	Fabrication (polishing) of PM	During assembly of PMA (after pads bonded)	Average up and down best Zero-G prediction	Easy Test at L-3 and BATC

λ = 633 NM

Optical Test Overview

- Vertical PMA Optical Testing
  - Final PM surface error
    - Average of looking up and looking down
- Interferometry comparison with FEA
  - Vertical PMA testing (looking up or looking down)
  - Horizontal Optical Axis Testing
  - Air bladder Testing
- Assure Correct Assembly
  - Counterweighted Zero-G Mount
    - Test PM
    - Test PM with bonded pads
    - Test PMA with bonded pads and struts

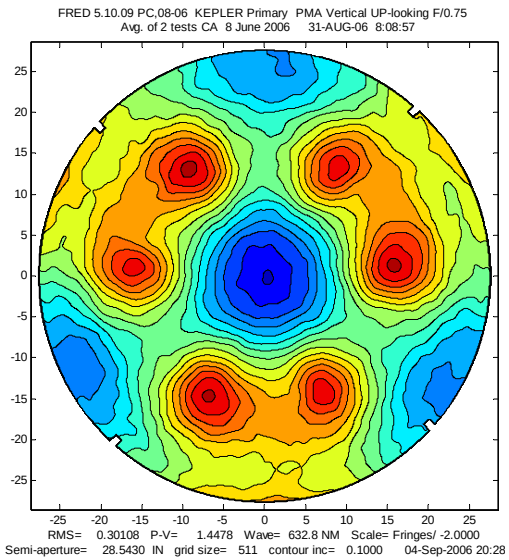
Vertical Test Tower

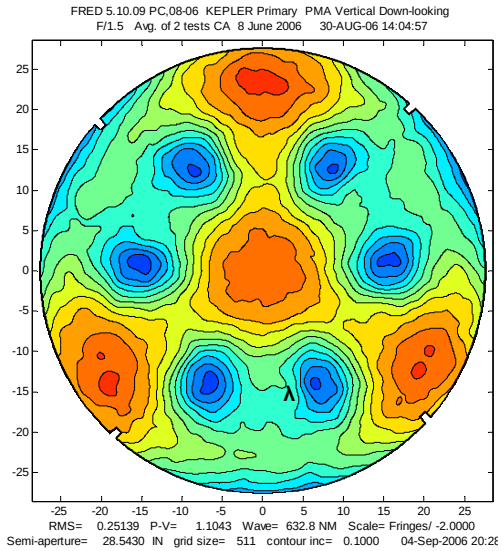
PMA Assembly

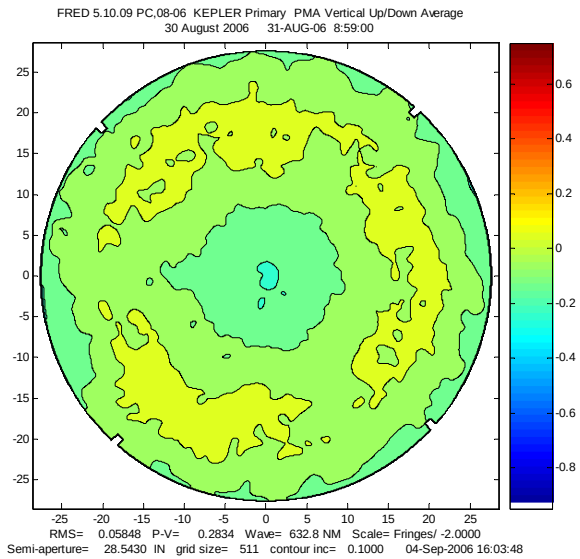
Vertical Test Tower

PMA Down-Looking

Vertical PMA Test for Fabricated Surface







Up Looking Test RMS 0.301

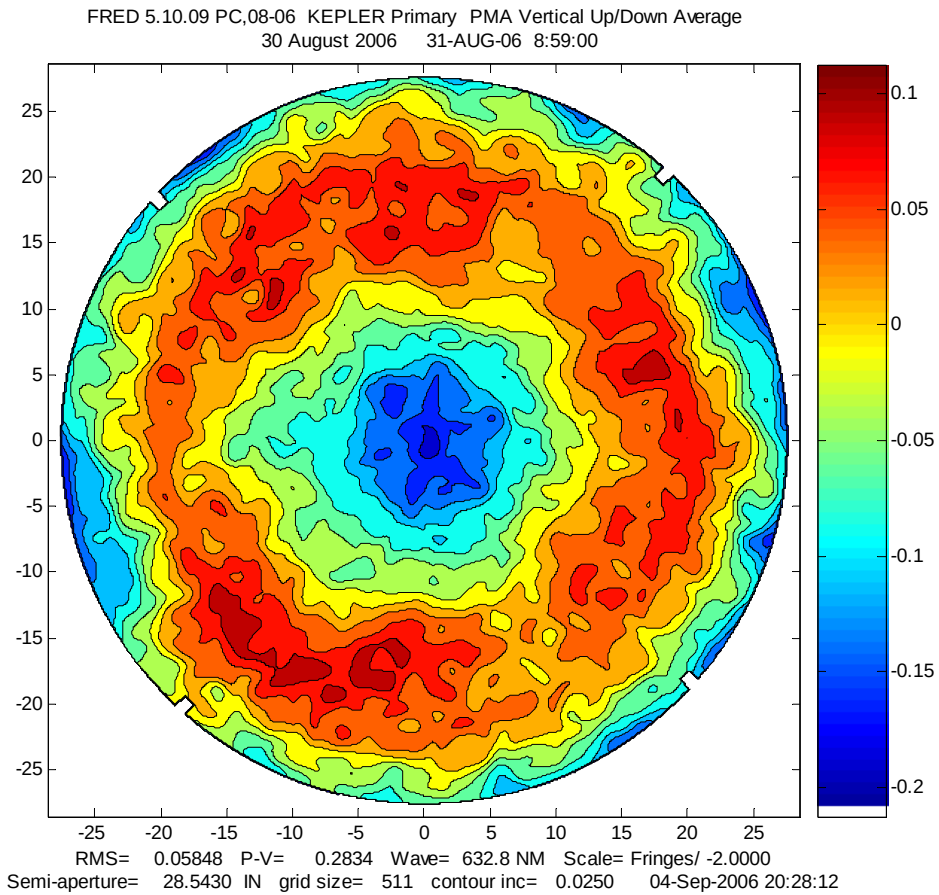
Down Looking Test RMS 0.253

Average = Surface Figure RMS 0.058

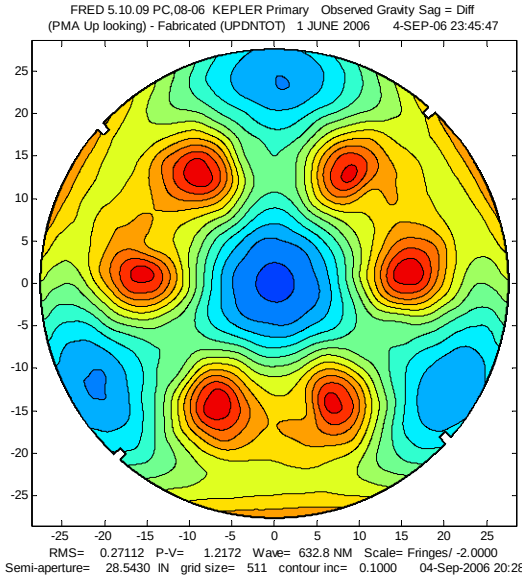
- **PMA coordinate system**
- **6 bonded pads support points evident in interferometric test**
- **Plot increment is 0.1 λ, at λ = 633 NM**

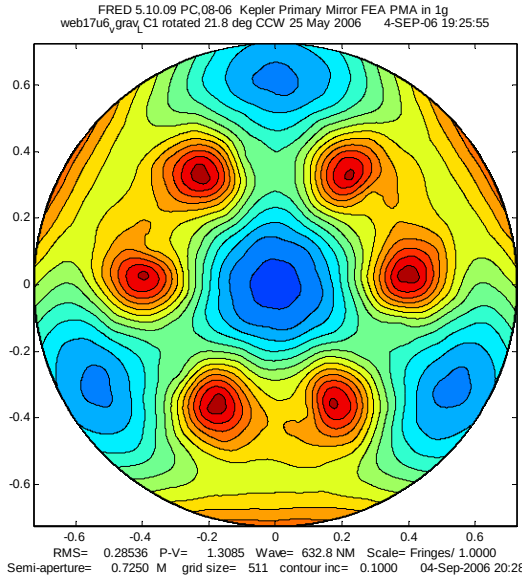
Final Fabricated Surface Figure

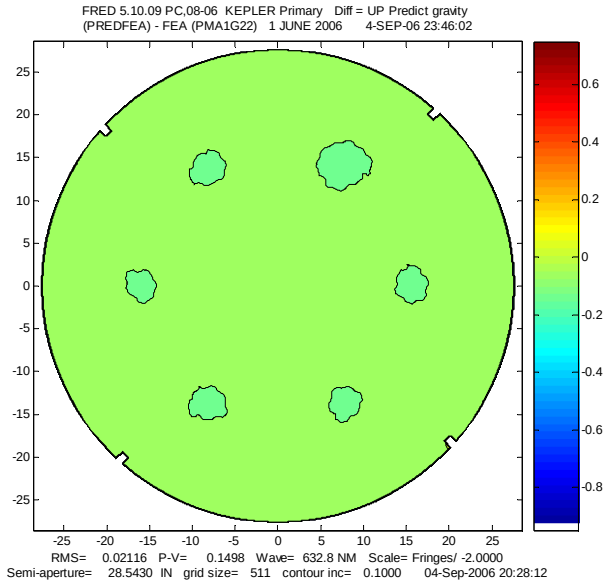
- Space Zero-G, ambient temperature, fabricated surface Figure
- Average of vertical testing
  - PMA up looking
  - PMA down looking
- PMA coordinate system
- Tested RMS 0.0585 λ
  - Wavelength = 633 NM
- Specification RMS 0.075 λ
  - Space Zero-G
  - Temp. = -5^{0}C to -55^{0}C
- Plot increment 0.025 λ



Vertical Up Looking Compared to FEA







Test – Fabricated Surface
RMS= 0.271

FEA Model
RMS= 0.285, PV= 1.31

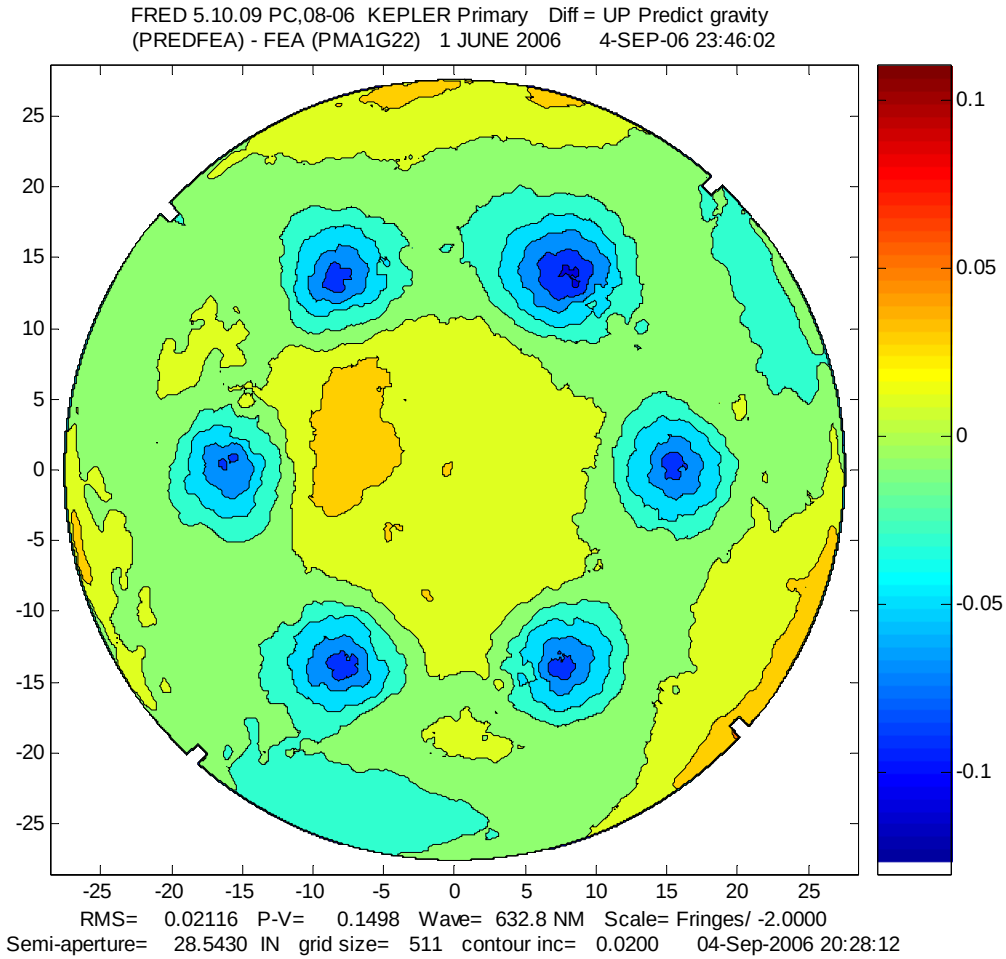
Difference = Model Error
RMS= 0.021

- **Interferometric Test – Fabricated Surface Error = Tested 1g**
- **FEA Model from ANSYS analysis is predicted 1g effect**
- **Difference is modeling error**
- **Contour increment 0.1 λ, λ = 633 NM * PMA coordinate system**

Up Looking Model Error

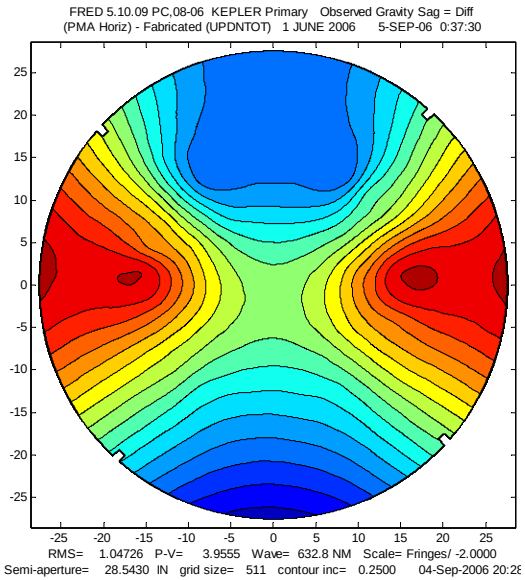
- RMS= 0.021 λ
- PV= 0.15 λ
- Plot increment= 0.02 λ
- λ = 633 NM

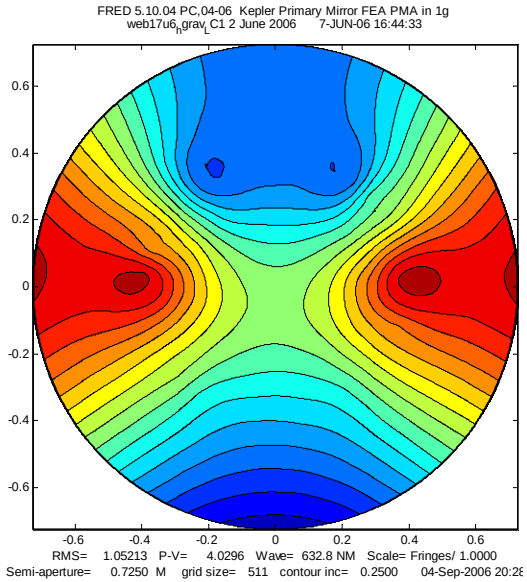
- RMS Error is 7.4%
- Largest error
  - Bond pad support points
- Model improvement
  - Higher density mesh

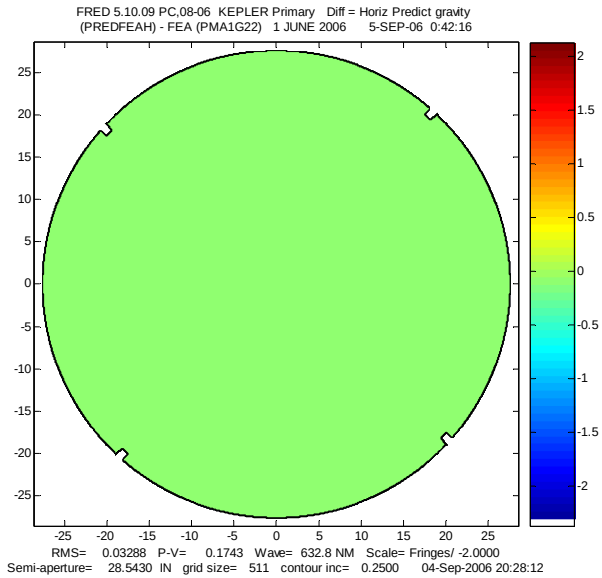


Kepler

Horizontal Test compared with FEA







Test – Fabricated Surface
RMS= 1.047

FEA Model
RMS= 1.052

Difference = Model Error
RMS= 0.033

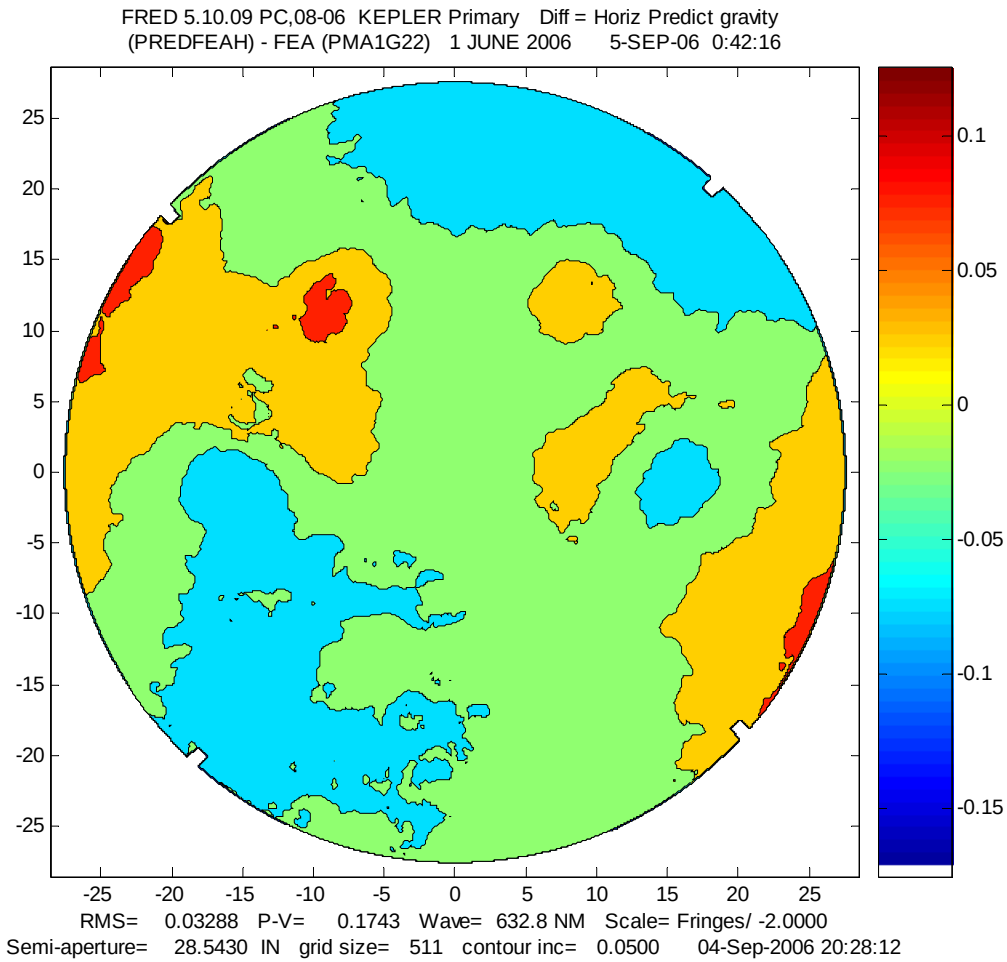
- **Interferometric Test – Fabricated Surface Error = Tested 1g**
- **FEA Model from ANSYS analysis is predicted 1g effect**
- **Difference is modeling error**
- **Contour increment 0.25 λ** *** PMA coordinate system**

Kepler

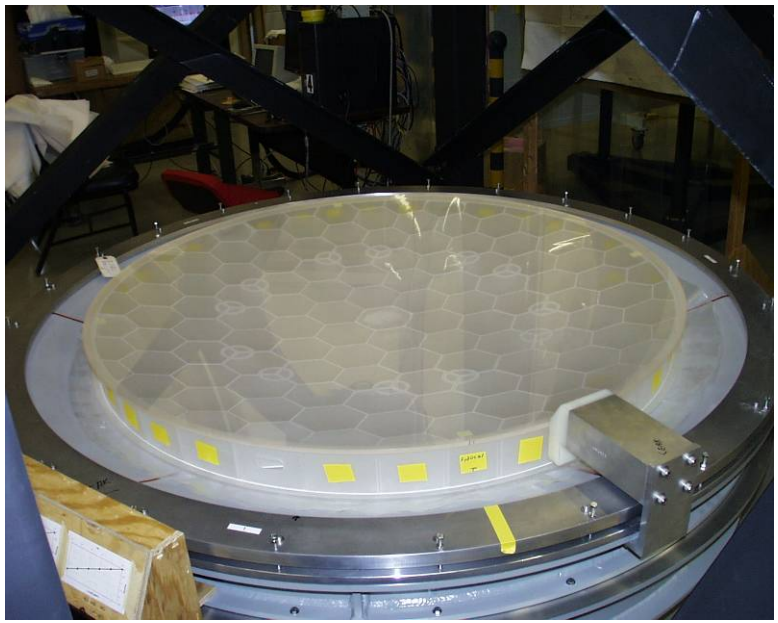
Horizontal Test Model Error

- RMS= 0.033 λ
- PV= 0.17 λ
- Plot increment= 0.05 λ
- λ = 633 NM

- RMS Error is 3.1%
- Model improvement
  - Bond pad support points
  - Higher density mesh
- Test improvement
  - Astigmatism from horizontal testing in air
  - Reduce thermal gradient - better mixing of air



Air Bladder Testing

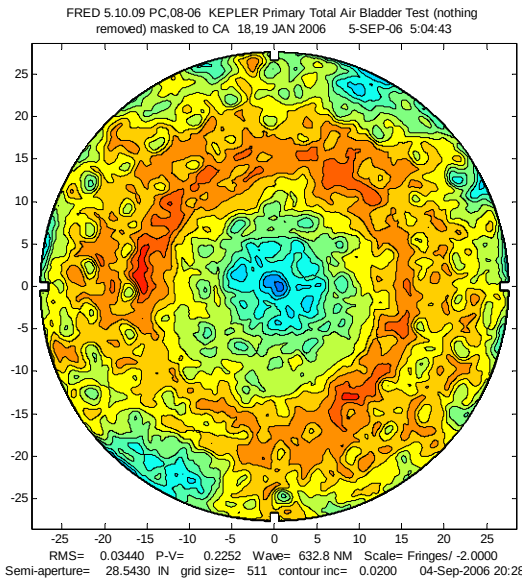


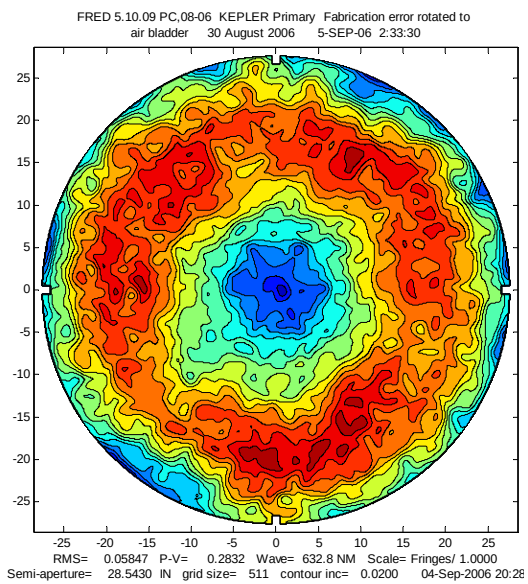
Air Bladder

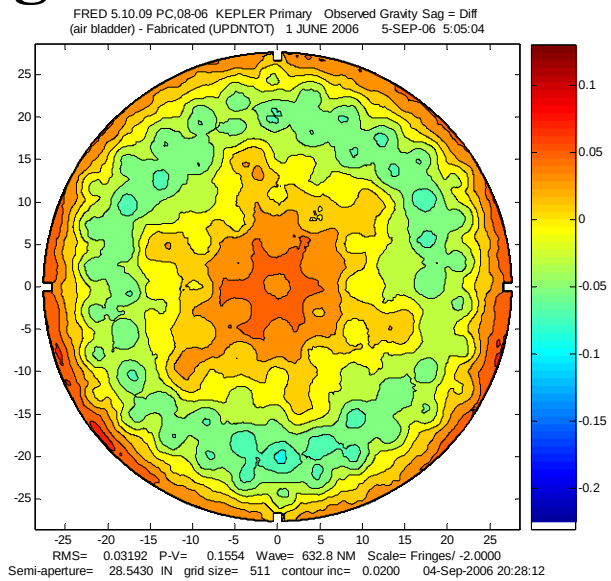
Test Tower

Interferometer on top

Air Bladder Testing







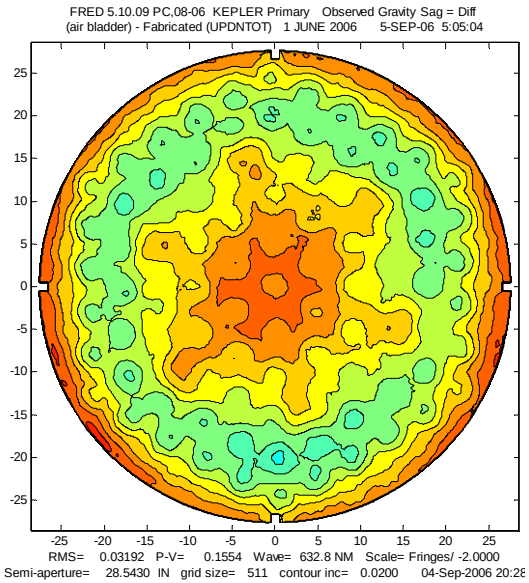
Air Bladder Test
RMS= 0.034

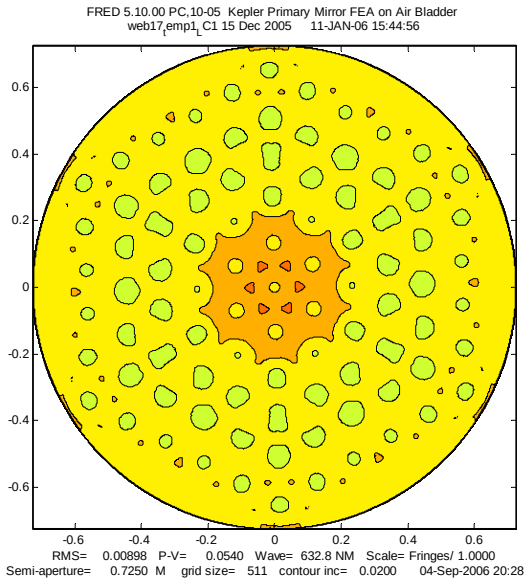
Fabricated Surface
RMS= 0.058

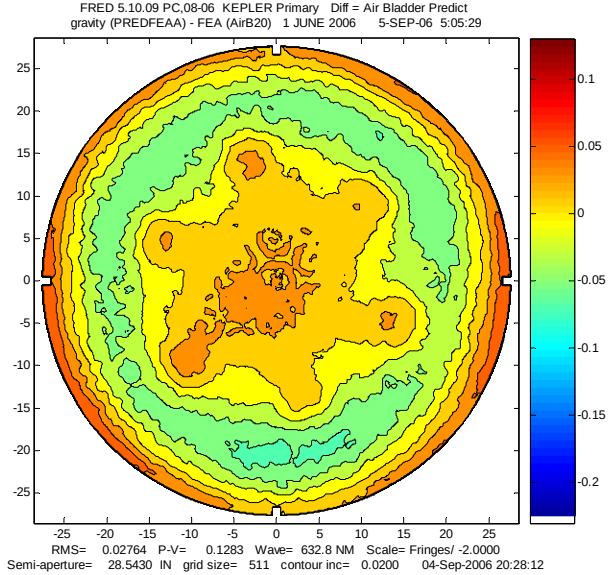
Difference is Predicted Gravity
RMS= 0.032

- **PM coordinate system = PMA rotated CCW 42.1 degrees**
- **Fabricated Surface from PMA UP and Down Average**
- **Plot increment= 0.02 λ**

Air Bladder Compared to FEA







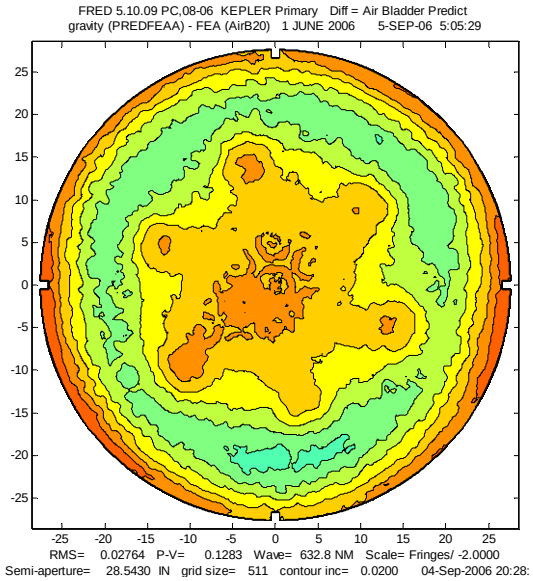
Predicted Gravity
RMS= 0.032

FEA Model
RMS= 0.0090

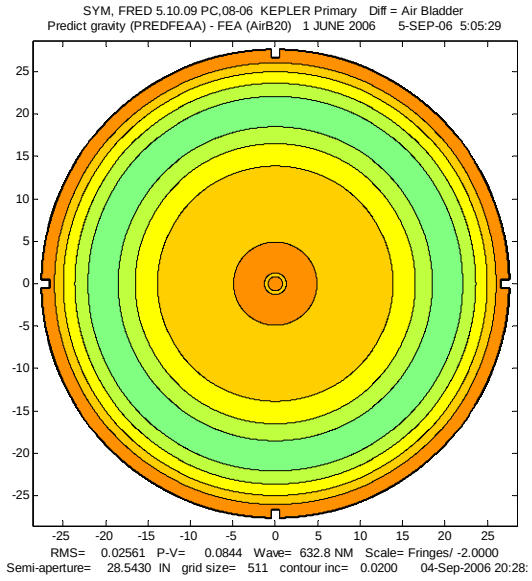
Difference is Model Error
RMS= 0.028

- **Model Error RMS= 0.028 λ**
- **Total Model Error is 311%**
- **Plot increment= 0.02 λ**
- **Model is adequate for fabrication Specification of 0.075 λ**

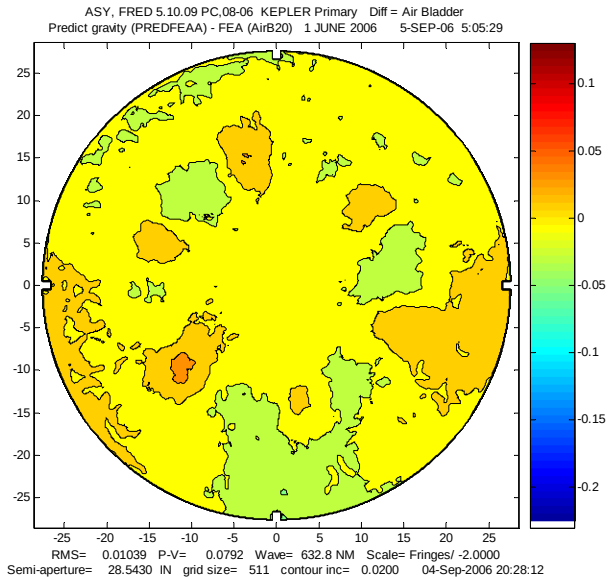
Air Bladder Model Error Interpretation



Model Error
RMS= 0.028



Symmetrical Error
RMS= 0.026



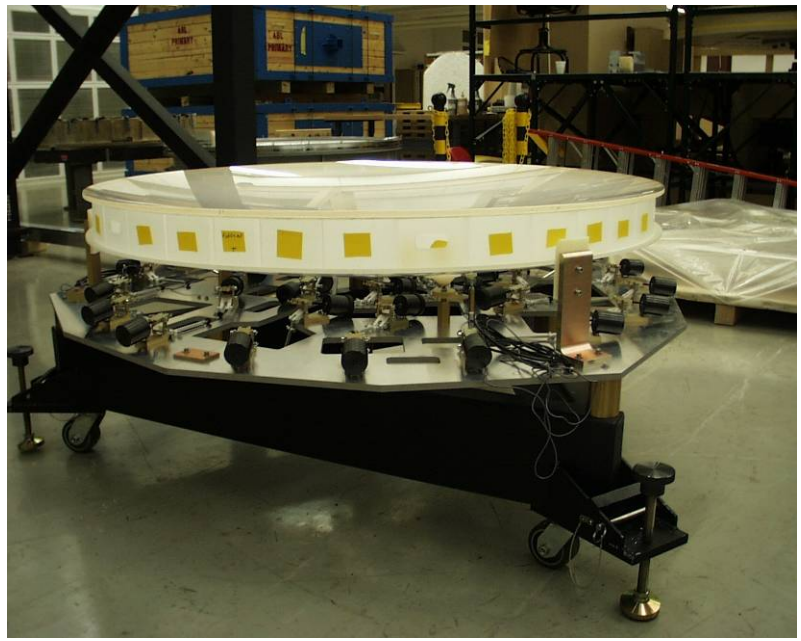
Asymmetrical Error
RMS= 0.010

- **Symmetrical error**
  - **OD edge problem due to bladder wrapping up side**
  - **Bladder does not fit curved PM back**

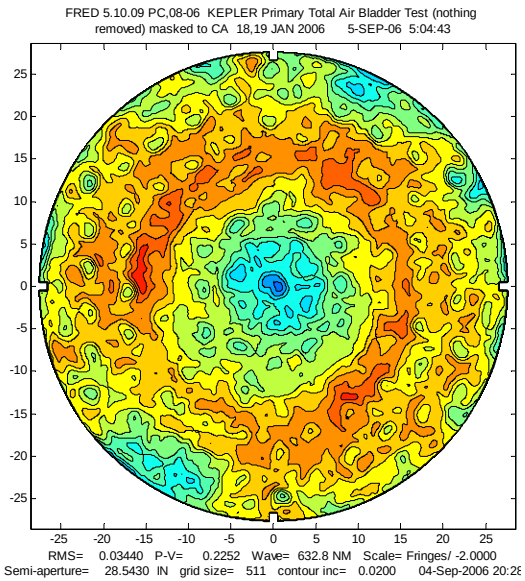
- **Asymmetrical error**
  - **Residual bond pad from vertical testing**
  - **Interferometry noise from large P-V and vibration**
  - **RMS expected noise level**

Counterweighted Zero-G Mount

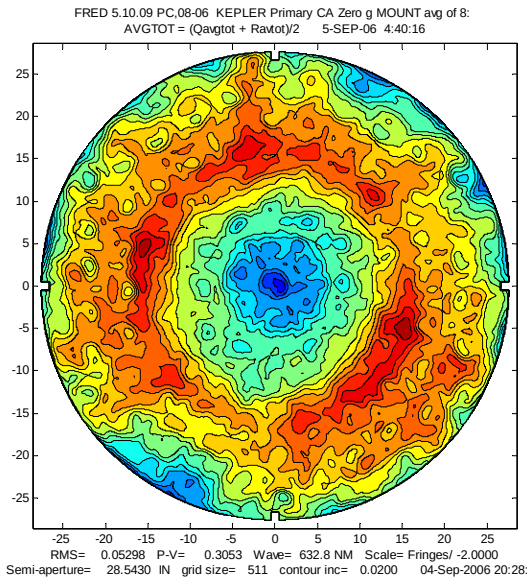
- Test during PMA assembly
  - Assure PMA is assembled with NO residual forces in PM from struts
  - Use PM coordinate system
- In process modification to mount improved results, but no FEA model
- Three Tests
  - PM on Zero-G Mount
  - PM with bonded pads on Zero-G Mount
  - Assembled PMA with Zero-G Mount



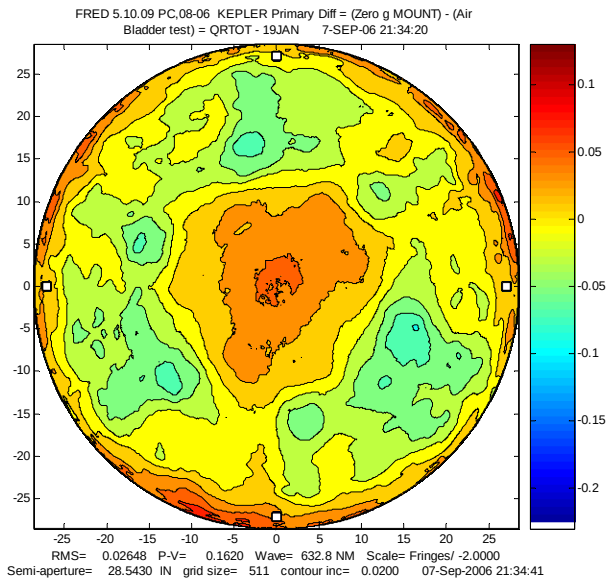
PM Test on Counterweighted Zero-G Mount



Air Bladder Test
RMS= 0.034



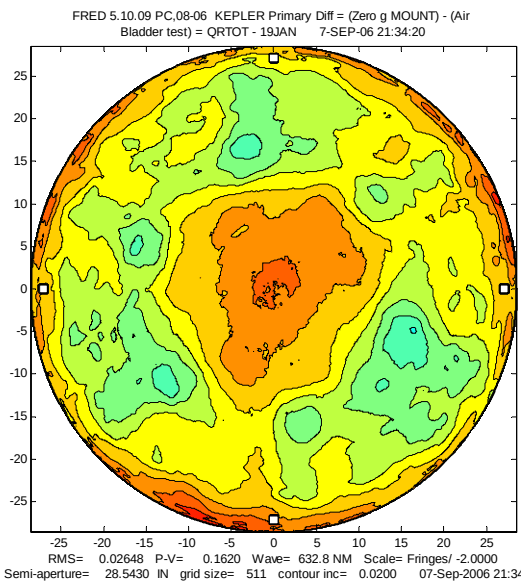
PM on Zero-G
RMS= 0.053



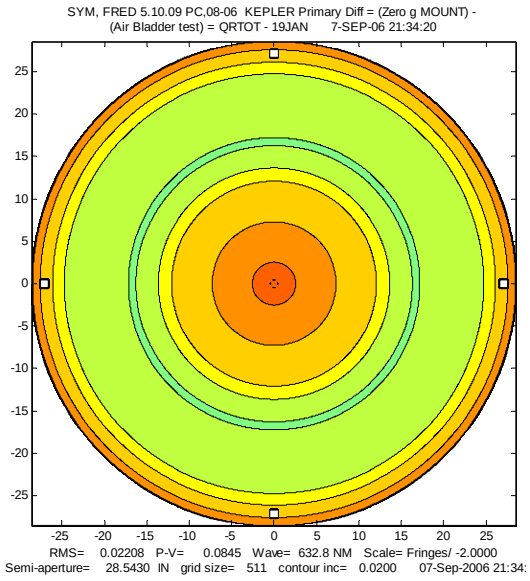
Difference
RMS= 0.026

- **PM coordinate system**
- **PM tested on Zero-G mount should be the same as the Air bladder test**
- **Plot increment 0.02 λ**

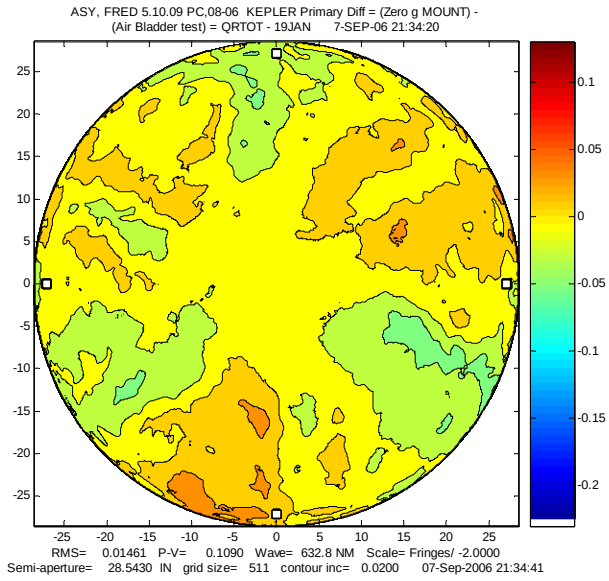
Zero-G Mount Difference Interpretation



Total Difference
RMS= 0.026



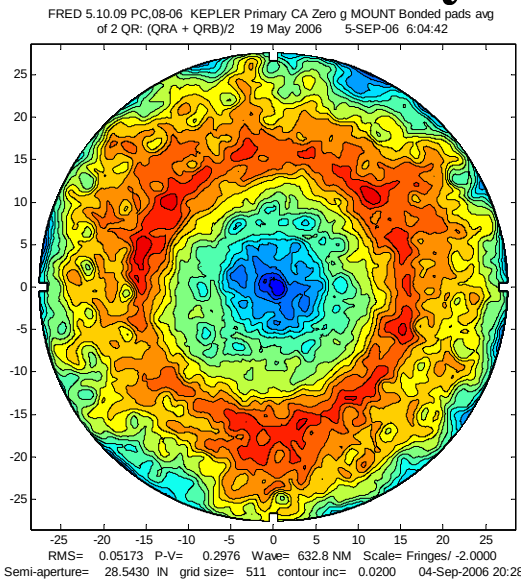
Symmetrical Difference
RMS= 0.022



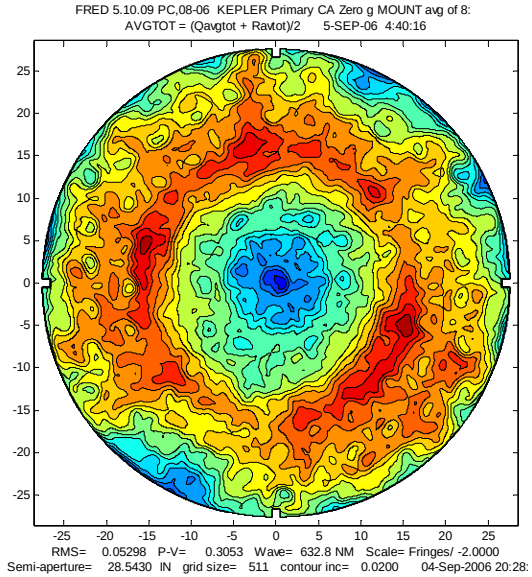
Asymmetrical Difference
RMS= 0.015

- **Symmetrical error is similar to Air bladder residual**
- **Asymmetrical is mostly Zero-G mount error**
  - **Assembly and implementation of counterweights**
  - **Non uniform mass distribution in fabricated PM**

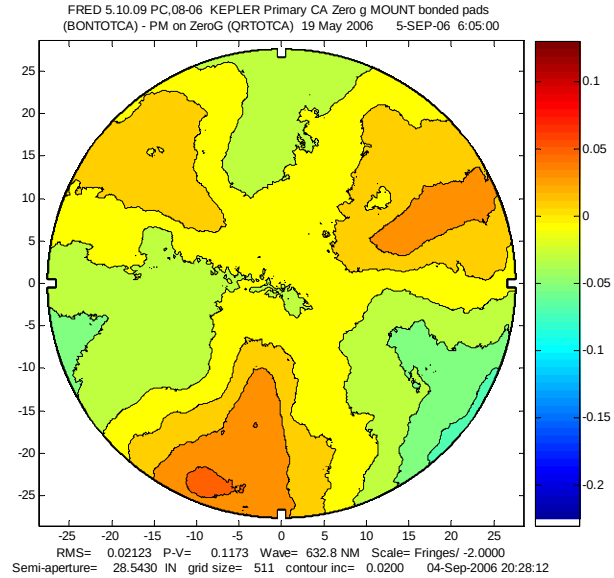
Assembly of PMA - PM with Bonded Pads



PM with bonded pads
RMS= 0.052



PM on ZeroG
RMS= 0.053

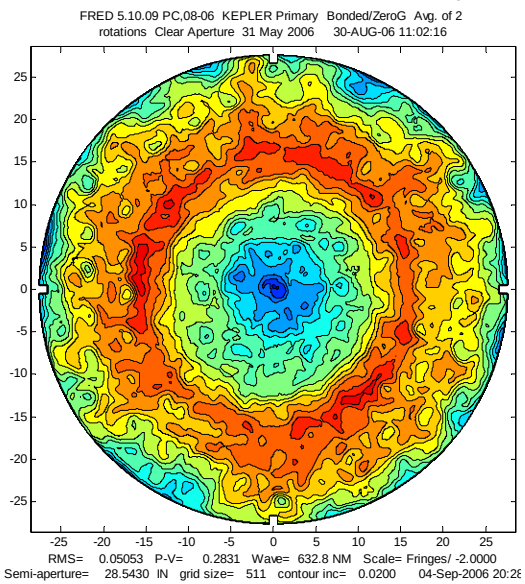


Difference
RMS= 0.021

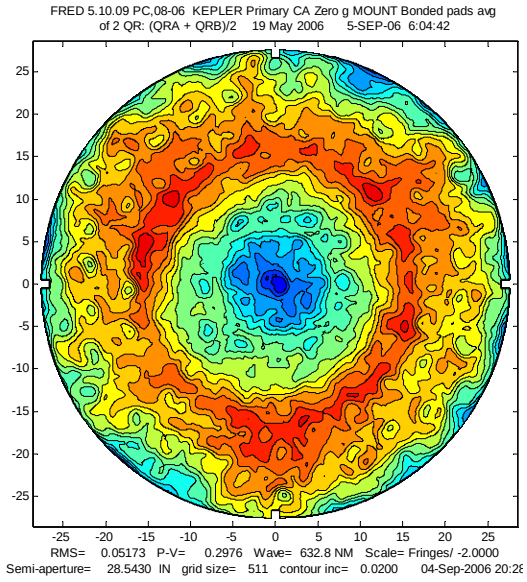
- No evidence of bonded pad adhesive cure print through
- Plot increment 0.02 λ
- Difference is all asymmetrical - third harmonic
  - After bonding pads had to rotate PM by 60 degrees
    - Conflict between ZeroG mount and Bonded pads
    - Mount error is ½ or RMS = 0.010 λ

* PM coordinate system

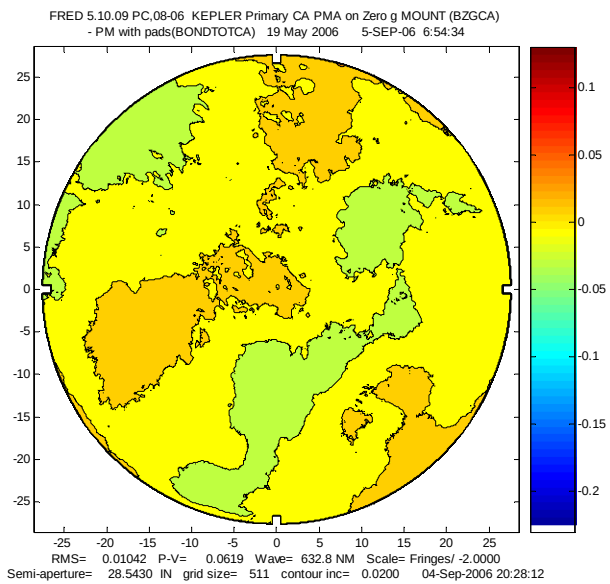
Assembly of PMA struts on Zero-G Mount



PMA on ZeroG
RMS= 0.051



PM with bonded pads
RMS= 0.052



Difference
RMS= 0.010

- **Difference shows NO evidence of residual forces from assembly of PMA**
- **RMS error is expected noise level in data**
- **Plot increment 0.02 λ**

*** PM coordinate system**

Conclusions

- **Design and analysis of PM and Test tooling was challenging but analysis and testing demonstrated to be adequate for our specification**
- **Excellent agreement of FEA analysis of PMA with interferometric test results**
  - **Vertical PMA testing error is 7.4%**
  - **Horizontal PMA testing error is 3.1%**
- **Air Bladder Modeling errors and implementation errors adequate for fabrication**
  - **RMS error 0.028 λ**
  - **Better implementation of air bladder at OD of mirror will significantly improve this symmetrical error**
- **PMA was assembled correctly**
  - **Testing noise < 0.010 λ RMS**
  - **Counterweighted Zero-G Mount testing showed surface figure repeatable did not change during assembly as desired**